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RESEARCH ARTICLE

^{15}N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated

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Abstract It is difficult to quantify nitrogen (N) losses from agricultural systems; however, we can use ^{15}N isotopic techniques to conduct site-specific studies to increase our knowledge about N management and fate. Our manuscript analyzes two reviews of selected ^{15}N isotopic studies conducted to monitor N fate. The mechanistic foci of these studies include crop residue exchange and N fate in farming systems. Analysis of the data presented in these studies supports the claim that the average N losses are greater from inorganic N fertilizer inputs than organic crop residue N inputs. Additionally we conducted unique DAYCENT simulations of the effects of crop residue on nitrous oxide (N_2O-N) emissions and nitrate (NO_3-N) leaching. The simulation evaluations support the crop residue ^{15}N exchange studies and show lower leaching and N_2O-N emissions from crop residue sources when compared to N fertilizer. The ^{15}N data suggest that the N in the crop residue pool must be recycled, and that this is a slower and more protected pool when compared to the readily available fertilizer. The results suggest that the Intergovernmental Panel on Climate Change (IPCC) methodology should be reevaluated to determine whether the direct and indirect N_2O-N emission coefficients need to be lowered to reflect fewer N_2O-N emissions from high C/N crop residue N inputs. The data suggest that accounting for nutrient cycling has implications for public policy associated with the United Nations Framework Convention on Climate Change (UNFCCC) and mitigation of N_2O-N emissions from agricultural soils. Additional crop residue exchange studies, field N_2O-N and NO_3-N leaching and support model evaluations are needed across different worldwide agroecosystems.

Keywords ^{15}N · Crop residue exchange · DAYCENT, IPCC · N_2O-N, nitrate leaching, nitrogen cycling

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Introduction

Several scientists have reported that excessive N inputs in cropland increase N losses, which impact groundwater (De Paz et al. 2009; Juergens-Gschwind 1989), large water bodies (Antweiler et al. 1996) air quality (Mosier et al. 1991), and contribute to Global Warming Potential (Mosier et al. 1991; Houghton et al. 1992; Eggleston et al. 2006). Better assessment of N cycling and the mechanisms used to reduce N losses will help increase N use efficiencies and reduce N losses to the environment (Delgado and Berry 2008; Delgado et al. 2007, 2008; Randall et al. 2008). Management practices can be used to better synchronize N inputs with crop uptake and reduce nitrate leaching (Meisinger and Delgado 2002) while mitigating N_2O-N and other N-gas emissions (Delgado and Mosier 1996; Mosier et al. 2002). Global concentrations of N_2O-N have been increasing at a faster rate in the last three decades (Houghton et al. 1992; Eggleston et al. 2006), and agriculture is responsible for a significant percentage of all anthropogenic emissions of N_2O-N. It is very important that we improve N management, because N inputs from crop residues and fertilizers account for a large proportion of greenhouse gas emissions (N_2O-N) from croplands soils; for example, over 30% of N_2O-N emissions in the United States are associated with sources of N (US EPA 2008). Accurate accounting of N cycling is also important when performing life cycle analyses for biofuel cropping systems and to rigorously assess the impacts of cropping on aquatic eutrophication.

The IPCC has recommended accounting for the fertilizer-N, manure-N, crop residue-N inputs, and N released via mineralization associated with soil organic matter losses (mineralization-N) when assessing direct and indirect emissions of N_2O-N (Eggleston et al. 2006). The IPCC's methodology assumes that 1% of fertilizer-N, crop residue-N, manure-N, and mineralization-N added to cropland are emitted to the atmosphere as direct emissions of N_2O-N. This methodology also assumes that 30% of the fertilizer N from these sources is leached and/or lost in runoff of water to streams and rivers, and 0.75% of this N is indirectly emitted as N_2O-N beyond the original site of the N additions (Eggleston et al. 2006; De Klein et al. 2006). It further assumes that 10% of the fertilizer and manure N applied to agricultural fields is lost through NH_3-N volatilization and NO_x-N emissions, and about 1.0% of this N is later emitted as N_2O-N. These methods have broad implications for domestic and international policy because countries use these approaches for reporting agricultural emissions of N_2O-N to the UNFCCC.

Recent studies have shown that we can reduce up to 50% of the traditional N fertilizer application rates and increase N use efficiencies, thereby reducing reactive N losses to the environment without reducing crop yields (Delgado and Bausch 2005; Delgado et al. 2005). For example, remote sensing and precision conservation techniques contributed to synchronized N fertilizers inputs with crop N uptake under commercial farming operations while reducing N losses to the environment by 47% (Delgado and Bausch 2005). The N inputs to grain corn (*Zea mays* L.) were cut by 45% without any reductions in grain yields (Delgado and Bausch 2005). Additionally, N inputs were cut by about 50% with controlled release fertilizers under commercial farming operations without reducing total potato tuber yields, thus reducing the maximum potential impact on the environment (Shoji et al. 2001).

Nitrogen use efficiencies of cropping systems can be measured with accurate isotopic ^{15}N techniques that allow us to trace the fate of N in the environment. It is important to conduct these ^{15}N crop residue studies under field conditions, because the interaction between crop uptake (roots), management practices, agricultural equipment, and the added N is not possible under a laboratory incubation. Interaction with weather variability, including the wetting and drying cycles in the field, as well as management must also be considered to conduct realistic research under commercial conditions.

The effect of agricultural land use activities on N_2O-N emissions can be assessed with field studies. Another approach to estimate the contributions of anthropogenic activities on N_2O-N emissions is the use of computer models such as DAYCENT (Del Grosso et al. 2001). This model is a tool that is used to calculate N_2O emissions for the U.S. Agriculture and Forestry Greenhouse Gas Inventory (Del Grosso et al. 2008b EPA 2008). Soil N_2O emissions are quantified by combining results from DAYCENT model simulations of major crops [corn, soy, wheat (*Triticum aestivum* L.), hay, cotton (*Gossypium* spp. L.), sorghum *Sorghum bicolor* (L.) Moench] with IPCC methodology for other crops.

Meisinger and Delgado (2002) reported that average leaching losses typically range from 10 to 30% of the total N input, in agreement with IPCC reports of leaching losses of 30%; however, they differentiated from IPCC assumptions in that they reported that crop residue cycling will contribute to lower nitrate leaching losses. They reported that adding a leguminous crop to a rotation and cover crops will reduce NO_3-N leaching losses. Al-Sheikh et al. (2005) reported that cover crop systems contributed to the sequestration of N. Cover crops could recover and reduce NO_3-N leaching from previous and subsequent crops including the mining of NO_3-N from groundwater (Delgado 1998; Delgado et al. 2001). This is in agreement with Delgado and Follett (2002) that reported that systems that increase soil organic matter accumulation and carbon sequestration will reduce NO_3-N leaching losses to the environment. The IPCC does not account for the positive effects of crop rotations and assigns the same NO_3-N leaching coefficient to N from fertilizer and crop residue.

Accounting for crop residue N cycling and N budgets is an essential component of best management practices, especially when there is potential for significant N cycling from crop residues such as vegetables, cover crops, and leguminous crops. It is important when assessing the effect of crop residues on N_2O-N emissions that the N inputs from the crop residue are credited, particularly when studying leguminous N-fixing crops. Otherwise, the studies will be skewed by excessive N fertilizer application, because the N cycling from the previous leguminous crop adds significant amounts of N to soils, which will increase the total N application and likely the total N_2O-N emissions as well.

Materials and methods used for crop residue studies

Delgado et al. (2004) described the procedure for monitoring the N inputs and cycling from crop residues using unique large ^{15}N plot studies. These large plots allow use of machinery to simulate agricultural practices and have been established in south central Colorado (Delgado et al. 2004) and Paterson, Washington (Collins et al. 2007). A mirror set of unlabeled N plots were established at each site and received similar management practices including the same amount of N fertilizer inputs with unlabeled N. The crops in both states were irrigated with center-pivot sprinkler irrigation and were grown in sandy coarse soils. The recovery and fate of the applied ^{15}N was monitored during the first year for wheat and barley (*Hordeum vulgare* L) in Colorado and for the cover crop, mustard (*Brasica hirta*) in Washington by collecting plant and soil samples from the initial ^{15}N labeled fertilizer plots. Bulk densities and other supportive measurements were used to estimate the total recoveries.

The aboveground ^{15}N-labeled crop residue was exchanged with the unlabeled residue following harvest of the ^{15}N-labeled cover crops (Fig. 1). Since the crop residue was labeled with ^{15}N, this exchange allowed the tracing of N fate from the crop residue into the following crop. The ^{15}N labeling also made it possible to quantitatively measure the N losses from crop residue to compare these values to those reported in previously published N fertilizer studies. For specific details about the order of exchange see Delgado et al. (2004) and Collins et al. (2007). All aboveground plant material was sampled by section to ensure the same ^{15}N labeled crop residue distribution during exchange with the unlabeled plots.

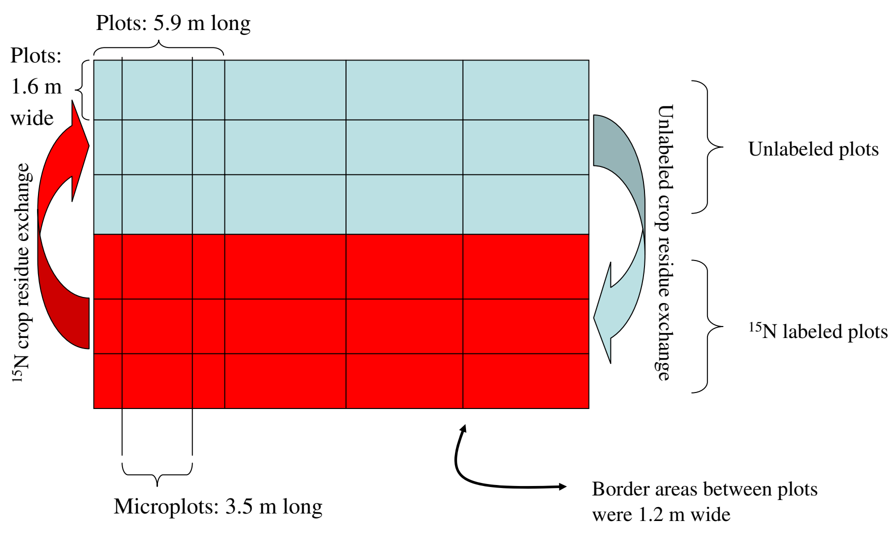

Fig. 1 Plot layout for the ^{15}N crop residue exchange study (Delgado et al. 2004)

Aboveground crop residue and soil samples were collected for isotopic analysis.

Potato (*Solanum tuberosum* L.) crops were planted following the cover crops in Colorado and Washington. At harvest, potato and soil samples were collected and analyzed for ^{15}N. Soil samples were extracted using 2N KCl and extracts and were analyzed for NO_3-N and NH_4-N with colorimetric analysis by a Technicon©1 auto-analyzer. Plant and soil material were analyzed for total N and ^{15}N atom% using a Carlo-Erba automated C/N analyzer coupled with a VG-903 mass spectrometer.

Modeling

A selected unique set of studies conducted across the USA where N_2O emissions were monitored were used to test the accuracy of the DAYCENT model (Table 1). The management, weather and soil information data from each of these studies were used to conduct DAYCENT model simulation of N_2O emissions and to correlate the simulated versus measured values (Fig. 2). For additional information about these sets of studies and how N_2O emissions were monitored and conducted in the field see Del Grosso et al. (2008a), Jarecki et al. (2008), Kessavalou et al. (1998), Robertson et al. (2000) and Thornton and Valente (1996). Since the model simulation values were correlated to the measured values we used the DAYCENT model to assess the effects of N fertilizer and crop residue inputs on N_2O emissions.

To test the effect of crop residue and/or fertilizer on N_2O emissions we used the DAYCENT model to conduct a simulation of: (1) dryland wheat–fallow rotation from northeastern Colorado; (2) corn–corn rotation from central Iowa and (3) corn–soybean (*Glycine max*) rotation from central Iowa. Conventional

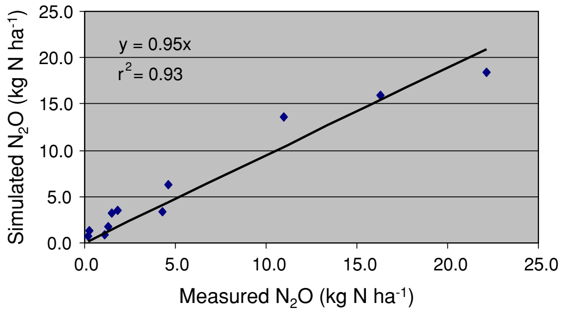

Fig. 2 DAYCENT-simulated versus measured N_2O emissions at different field sites that were used to test the model

farmer management practices and local weather data were used from each site (Del Grosso et al. 2008b; EPA 2008). The soil type in Iowa was a loam and in Colorado it was a sandy loam. Evaluations of the model scenarios to determine the effects of N fertilizer and crop residue on N_2O emissions were conducted with a decade of traditional management practices and site- specific weather. For Colorado, the site history was wheat/fallow (WF) with 70 kg N ha^{-1} added every other year and no residue harvested. For Iowa, the site history was assumed to be a corn/corn (CC) rotation and a corn/soybean (CS) rotation. The N fertilizer applied was 150 kg N ha^{-1} added every year to the CC and every other year to CS. For these simulations the N content in the crop residue removed was equivalent to about 40 and 20 kg N ha^{-1} for corn and wheat, respectively. The N fertilizer removed from the dryland WF rotation was 20 kg N ha^{-1} during the wheat year. Similarly, 40 kg N ha^{-1} annually was removed for the CC rotation and every other year from the CS rotation.

Since a leguminous crop is not fertilized and the soybean residue is traditionally left in the field, we kept the legume residue in the field for the corn-soybean simulation. The crop residue scenarios

Table 1 Characteristics of data used for model testing

State	Crop	Period monitored	Reference
Colorado	Dryland wheat/fallow	1993–1995	Mosier et al. (1997)
Colorado	Irrigated barley	1983	Mosier et al. (1986)
Colorado	Irrigated corn	1982	Mosier et al. (1986)
Colorado	Irrigated no till corn	2002–2006	Del Grosso et al. (2008a)
Michigan	Corn, soybean, wheat	1991–1999	Robertson et al. (2000)
Iowa	Corn, soybean	2006	Jarecki et al. (2008)
Nebraska	Dryland wheat/fallow	1993–1995	Kessavalou et al. (1998)
Tennessee	No till corn	1993	Thornton and Valente (1996)

simulated were: (1) aboveground crop residue kept in the field for the WF, CC and CS rotations (residue retained); (2) removing aboveground corn and wheat residue for the WF, CC and CS rotations (residue removed); and (3) aboveground crop residue kept in the field but removing a similar amount of N from the fertilizer input for the fertilized corn and wheat for WF, CC and CS rotations (residue retained, decreased fertilizer).

Results and integration of these studies

Analysis of unique ^{15}N crop residue studies

Table 2 presents the results of the analysis of published crop residue ^{15}N exchange studies. The analysis of this ^{15}N data clearly shows that the 31% N losses from the inorganic fertilizer inputs were significantly higher than the 13% N losses from the crop residue inputs. It is also apparent from these studies that the 26% of fertilizer N retained in the soil was much lower than the 73% of crop residue N retained in the soil.

The data also show higher availability, mobility and transformation of the applied N fertilizer that quickly enters the available N pool for crop uptake. The average crop uptake was 43%, much higher than the 14% measured from the crop residue inputs. However, the readily available fertilizer-N is also susceptible to faster dynamics that resulted in greater average N losses of 31%. The slower crop residue N input depends on microbial activity for transformation into a plant-available form and averaged 13% N losses. The data from these large-plot ^{15}N fertilizer and crop residue exchange studies show that N losses from inorganic fertilizer input is two and half times higher than N losses from organic crop residue input. The 31% N losses from inorganic fertilizer reported in Table 2 is in agreement with the ^{15}N losses from inorganic fertilizer across 22 international studies reported by Randall et al. (2008).

Analysis of these ^{15}N studies demonstrates that, on average, the N release from crop residues will incur lower levels of N loss. We suggest that the release of N from the particulate organic matter and crop residues will better match the timing of crop growth and N uptake, and will result in lower levels of N loss than occurs with N fertilizer application.

Modeling evaluation of N_2O emission from crop residue and inorganic N fertilizer

The modeling exercise is in agreement with the results from the unique ^{15}N crop residue studies. The simulated N losses to the environment were much lower from the wheat and corn crop residue than from the N fertilizer. By removing the N fertilizer the N_2O-N emissions and NO_3-N leaching are reduced significantly, suggesting that an increment of 20–40 kg N ha^{-1} will increase these losses significantly. Contrary to the value calculated with current IPCC coefficients, the removal of crop residue and an equivalent amount of N fertilizer, increases both N_2O-N emissions and NO_3-N leaching. We suggest that these increases are due to a lower N immobilization. These high C/N residues “tie up” available N and sequester N in the soil organic matter (Delgado et al. 2004;

Table 2 ^{15}N applications, recoveries and losses in irrigated cover crop studies

Location	Crop	N source	Applied ^{15}N (kg N ha^{-1})	Soil recovery (% ^{15}N)	Plant recovery (% ^{15}N)	Lost (% ^{15}N)
Colorado	Wheat[a]	Fertilizer	95	27	47	26
	Potato[b]	Wheat residue	37	79	7	14
Colorado	Wheat[a]	Fertilizer	95	25	49	26
	Potato[b]	Wheat residue	41	79	6	15
Colorado	Barley[a]	Fertilizer	95	28	40	32
	Potato[b]	Barley residue	35	69	13	18
Washington	Mustard	Fertilizer	56	24	34	42
	Potato[c]	Mustard residue	142	66	29	5
Average		Fertilizer		26 ± 2	43 ± 7	31 ± 8
		Crop residue		73 ± 7	14 ± 11	13 ± 6

[a] Received an additional 28 kg unlabelled fertilizer-N ha^{-1}

[b] Received 135 kg unlabelled fertilizer-N ha^{-1}

[c] Received 375 kg unlabelled fertilizer-N ha^{-1}

Al-Sheikh et al. 2005). The simulated NO_3-N leaching losses increased during the fall and early spring at snow melt, when more corn residue was removed from the CS rotation than from the CC rotation.

These simulated results contradict the assumptions of similar loss coefficients for N fertilizer and crop residues N for N_2O-N emissions and NO_3-N leaching. We respectfully propose that it is necessary to revise these IPCC assumptions to clarify the effects of nutrient cycling (mobilization/immobilization) on N_2O-N emissions and leaching losses. We further postulate the hypothesis that crop residues could contribute to lowering N_2O-N emission and NO_3-N leaching losses, especially if they have high C/N ratios. Contrary to what the IPCC assumptions show for higher C/N ratios, removing the 40 kg N ha^{-1} from crop residue does not lower the N_2O-N or NO_3-N leaching losses; rather, it increases these losses.

These simulation results for the WF, CC and CS rotations are in agreement with the ^{15}N crop residue studies by Delgado et al. (2004) and Collins et al. (2007). Simulation results are also in agreement with findings by Delgado and Follett (2002) that by adding or increasing soil organic matter (adding crop residue), the N and NO_3-N leaching losses will be lowered due to a sequestration of N in the soil organic matter. We suggest that these high C/N ratios residues are among the factors that contribute to immobilizing N and sequestering N in the soil (Fig. 3). The data suggest that by keeping a high C/N ratio residue in the field, the N_2O-N emission will be lowered (Fig. 3). This is also in agreement with crop residue incubations conducted by Toma and Hatano (2007) that found that high C/N residues immobilize N and reduce N_2O-N emissions. These results are further supported with Delgado (1998), Delgado et al. (2001), Delgado and Follett (2002) and Meisinger and Delgado (2002) nitrate leaching management principles that under a rotation system that includes scavenger crops, adds crop residue to the system, and increases soil organic matter, the NO_3-N leaching will be reduced and N will be sequestered (Al-Sheikh et al. 2005).

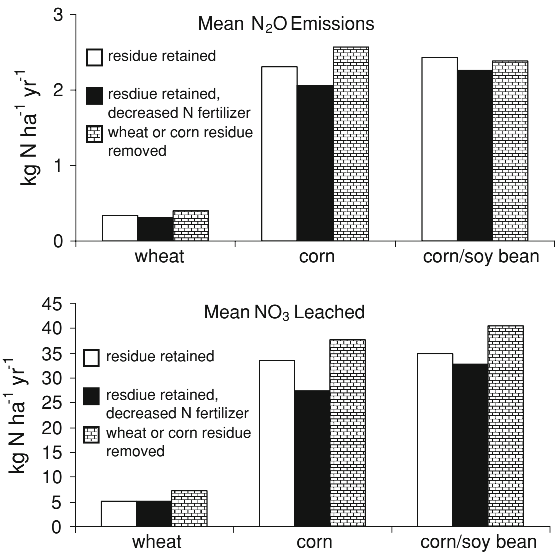

Fig. 3 Mean Nitrous Oxide (*N_2O*) and nitrate leaching (*NO_3-N*) from a 10 year site specific simulation of a dryland wheat–fallow rotation in Colorado (wheat); corn–corn rotation in Ohio (corn) and a corn–soybean rotation in Ohio (soy). The simulated scenarios were (*1*) aboveground crop residue kept in the field (residue retained); (*2*) removing aboveground crop residue (residue removed); and (*3*) aboveground crop residue kept in the field but removal of a similar amount of N from the fertilizer input (residue retained, decrease fertilizer)

Summary and conclusions

The ^{15}N analysis presented in Table 2 and N_2O simulations in Fig. 3 are in agreement with several recent papers that studied the effects of crop residues on N_2O-N emissions. Malhi and Lemke (2007) conducted 8 years of studies in Canada to assess the effect of crop residue and N fertilizer inputs on N_2O-N emissions. They reported that straw management, a treatment that was referred to as *no straw* or *straw removed from plots*, had no effect on the N_2O-N emissions. They concluded that this was important because the IPCC reports that crop residue contributes to N_2O-N emissions. Another recent study conducted by Toma and Hatano (2007) found that the effect of crop residue from wheat and rice straw on N_2O-N emissions was minimal, while the N_2O-N emissions from soybeans and onions were significantly higher.

These data sets suggest that the IPCC's N_2O-N emission assessment methodology should be reevaluated, because there are differences in N use efficiencies of the crops (recoveries in soil and plant) between N fertilizer and crop N residue inputs, and consequently the methods should use different N_2O-N emission coefficients for inputs from the readily available inorganic N fertilizer and from the slower, microbe-dependent crop residue N inputs (Table 2; Fig. 3). Accounting for these differences in N cycling within soils has far-reaching consequences for N_2O-N emission inventories reported by countries, including established baselines and meeting mitigation commitments agreed upon through the climate change convention. We suggest that the leaching losses from crop residues will be lower than those from fertilizers; thus, the indirect N_2O-N emission from crop residue will also be lower.

Our results are consistent with recent research showing that although the default IPCC methodology used to calculate N_2O-N emissions from agriculture is reliable at large scales, the attribution of these emissions to specific fields or N sources may not be appropriate (Del Grosso et al. 2008c). The data presented in Table 2 and Fig. 3 suggest (pending additional data collection) that the IPCC crop residue N_2O-N emissions and NO_3-N leaching coefficients should be lowered (Delgado and Follett 2002; Malhi and Lemke 2007; Toma and Hatano 2007).

Several other scientists have also reported that N_2O-N emissions from crop residues are lower than the 1% reported by IPCC (Jantalia et al. 2008). Other data suggest that the average total N_2O-N emissions from corn–soybean were lower than from corn–corn. However, when the N_2O-N emissions were divided by the total N inputs to the system, the corn-soybean had higher N_2O-N emissions per N inputs from fertilizer and crop residue, suggesting that leguminous crop residues affected N_2O-N emission rates (Adviento-Borbe et al. 2007).

Analysis of these ^{15}N crop residue studies and simulated crop residue scenarios, especially those for high C/N crop rotations such as wheat and corn, suggests that the national inventories submitted to the UNFCCC may be overestimating the effect of N inputs from crop residues on direct and indirect N_2O-N emissions relative to mineral N fertilization, based on the IPCC methods and default coefficients (Eggleston et al. 2006; De Klein et al. 2006). In turn, this overestimation will lead to policy which does not properly address the direct and indirect source of the N_2O-N emissions, and mitigation efforts that do not produce the results suggested by emission calculations conducted using the IPCC method. Such accounting of emissions would not be desirable as countries deal with the growing N_2O-N emissions associated with mineral N fertilization in agricultural lands, and attempt to reduce anthropogenic impacts on the Earth's climate system. Use of N cycling such as those from cover crops and deep rooted systems may be an alternative method to reducing direct and indirect N losses to the environment while increasing N use efficiencies (Delgado 1998; Delgado et al. 2001, 2004, 2008; Collins et al. 2007). In order to maximize the benefits from cover crops, introduction for a leguminous crop and deep rooted crops systems, better N budget practices that account for nitrogen cycling should be implemented. This paper clearly shows that there is a need for additional nutrient cycling research and that this research could affect policies of the United Nations and individual countries that relate to our biosphere as far as the accountability of trace gases such as N_2O-N.

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